Optimisation of Optical Directional Couplers for PCB Integration

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***Abstract*—An optimisation technique for optical directional couplers used for bidirectional data transmission within diffusion waveguides is presented. The coupler separates received and transmitted signals of the bidirectional waveguide. Efficiency optimisation of one direction of transmission, however, comes with the downside of a decline of efficiency in the other direction. We describe possibilities to antagonise this effect by extracting essential parameters that influence the efficiency.**

I. Introduction

Growing data rate in modern computer systems evokes the need for high speed transmission on board level in the near future. Therefore, research institutes dealt intensively with optical intra-board communication, in recent years [1], [2]. A promising approach is the use of optical waveguides in thin glass sheets, manufactured by diffusion processes [3] and integrated as an additional layer in the electrical boards. To save space on the board level a new approach is the use of bidirectional optical transmission on a single waveguide. It should be possible to integrate it into the current manufacturing process and have high transmission efficiency. We analyse the efficiencies of such a device and optimise it by finding critical influencing parameters.

II. Coupler Design

In [4] a bidirectional optical coupler for plastic fibres is presented. The general idea, however, can be easily transferred to optical waveguides produced by a diffusion process. In figure 1 the principle layout of such a coupler is presented. A waveguide attached to port 1 would contain both directions of transmission. In the branching area the coupling itself should take place: Signals transmitted from the sender at port 3 should be coupled into the waveguide with high efficiency and signals entering the coupler from port 1 should reach the receiver at port 2 without loss. The presented structure serves as mask for the diffusion process. Therefore, the parameters of the mask determine mainly the parameters of the generated waveguide. An analysis of these and their influence on the efficiency leads to a better understanding of the coupler and the possibility of designing it according to the needs of its application.

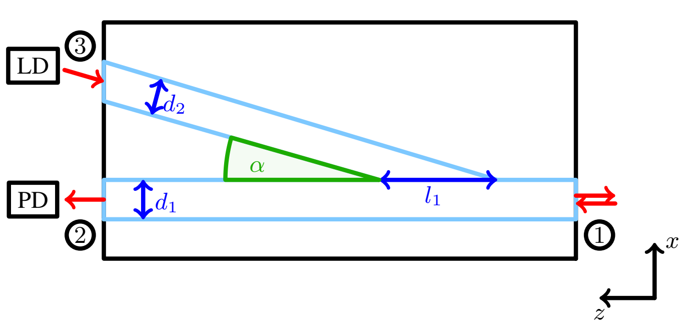

Fig. 1. Simplified mask structure of directional coupler

III. Mathematical Methods

We calculated the couplers' refractive index profile by solving the diffusion equation numerically with Finite Element Method [5], as an analytical solution is usually only achievable for special geometrical symmetries.

For our efficiency calculations we chose ray tracing, a method often used for loss calculations of highly multimodal waveguides [6], [7], as analysis of optical waveguides based on ray tracing is efficient for waveguide dimensions, which are large compared to the optical wavelength [8]. The crucial step is the solution of the ray equation

$$\frac{\mathrm{d}}{\mathrm{d}s}\left(n\frac{\mathrm{d}\mathbf{r}}{\mathrm{d}s}\right) = \nabla n(\mathbf{r}). \tag{1}$$

We modelled the excitation of the coupler with a ray intensity as a Gaussian distribution according to the position and a uniform distribution according to the angle of incidence in the range of the local numerical aperture to use the full angular spectrum of guided rays.

IV. Analysis and Optimisation

In a first step we modified two parameters of the mask structure, namely d_2 from a width of $10\mu m$ to $40\mu m$ and the angle α from $5°$ to $15°$ with a fixed value of $d_1 = 40\mu m$. For calculating the efficiency of the coupler we defined two directions of transmission: efficiency of the receiving direction was the ratio of rays entering the coupler at port 1 and reaching port 2. Efficiency of the transmitting direction was defined by the ratio of rays entering the coupler at port 3 and reaching port 1. Figure 2 shows the calculated efficiency in receiving direction with red dots. As shown by the smoothing fit in blue, it is quite remarkable, that the efficiency is almost optimal with angles greater than $10°$. Furthermore, an increase of efficiency with smaller widths of d_2 can be identified. Here, the smaller total width of the coupler's mask at the branching area causes a decreased maximum refractive index in the very same and thus a better uncoupling of the two branches. The calculated

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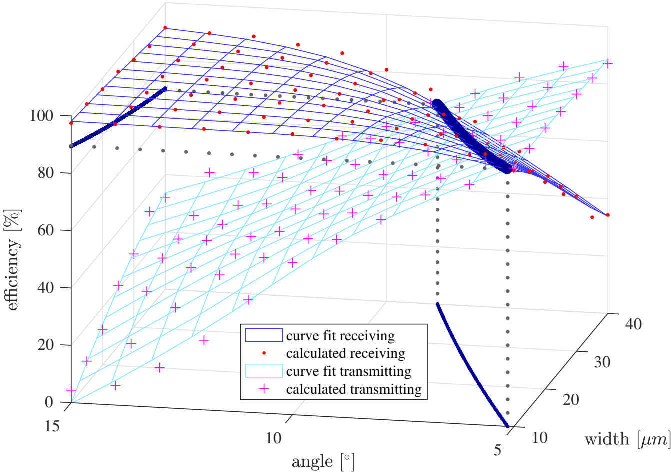

Fig. 2. Calculated efficiencies of directional coupler

efficiency in transmitting direction is presented in figure 2 with the magenta coloured markers. The opposing trend with regard to the receiving efficiency is obvious as shown by the light blue fit. The higher the angle α, the higher the losses. As the coupler should have high efficiencies in both directions, one has to find a compromise according to the chosen parameters α and d_2. The dark blue intersection line marks the area, where both directions have the same efficiency.

For an improvement of efficiency in receiving direction we demonstrated in [9], that the couplers properties in receiving direction could be easily improved by inserting a mask gap at the branching area, as this would uncouple the branches. Nevertheless, efficiency in transmitting direction dropped dramatically. For a mask gap of $30\mu m$ efficiency would decline by about 20% compared to the non gap case. In [10] a design for an optical directional coupler, manufactured by ion exchange process, was presented. The device was, due to its dimensions, used for monomode transmission. We investigated the very same idea for our multimode waveguides [11] to resolve the problem of bad efficiency in transmitting direction. The results proved to be promising. Figure 3 shows the mask structure of our approach. It was divided in two main parts, namely an S-bend waveguide, which was used to bring the transmitting branch close to the coupling area, overcoming a distance w_1 between the two branches and a coupling area with a distance w_2 between the branches and a tapered end of length l_k. We chose the bend structure, as an angled mask structure proved to be less efficient. By enhancing the bend radii, the bend waveguides losses could nearly be exterminated. This, of course, came with the downside of larger coupler dimensions. The coupling area itself showed good properties with increasing tapering lengths l_k. For the mask gap w_2 of $30\mu m$ mentioned above, efficiency increased by 35%, which is even better than without a mask gap. Efficiency in receiving direction, on the other hand, was still good despite of the mask modifications.

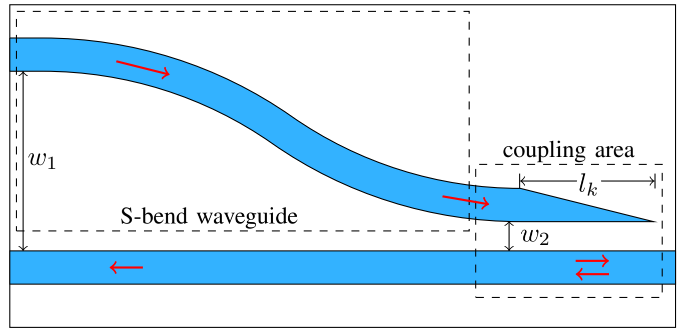

Fig. 3. Optimised coupler structure

V. Conclusion

We demonstrated a study of the manufacturing of a directional coupler with a diffusion process. The efficiency is remarkable even without further improvements of the manufacturing process. However, by uncoupling the branches and modifying mask curvatures, efficiency could be enhanced massively, especially in transmitting direction. To find an optimal mask structure for manufacturing, further intensive parameters studies of bend curvature and radii as well dimensioning of coupling length and corresponding mask gap will follow up.

Acknowledgement

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